Integrated modelling of lakes in the climate system - a summary from ASLO Granada and more

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with contributions from (only first authors of contributions mentioned here)

Thomas Bueche, Gideon Gal, Stéphane Goyette, Annette Janssen, Elisa Lindgren, Sally MacIntyre, Marjorie Perroud, Wim Thiery, Marco Toffolon, Koji Tominaga, Lijuan Wen

7 May 2015 | Lake2015

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Integrated modelling of lakes in the climate system - a summary

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Annette Janssen	Netherlands Institute of Ecology, Wageningen Netherlands
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Wim Thiery	Division of Geography, KU Leuven, Belgium
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4th workshop on “Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling”, Évora, Portugal, 7. – 9. May 2015

Contents of presentation

Integrated Lake Modelling in the Climate System
Lake Ice Dynamics

- were two sessions at the
  ASLO conference in Granada Feb. 2015

- attracting each 12 presentations ranging from
  - modelling hydrodynamic processes in lakes,
  - coupling with ecosystem models,
  - running multi-lake and multi-model approaches, and
  - coupling with regional climate models

Here we present a subset of presentations, where only a snapshot for each can be shown.
Abstracts of all presentations are available as pdf file.

Contents of presentation

Part I – ASLO presentations

- 10 selected presentations
- Summary

Part II – LakeMIP projects

- 4 new projects
- community publication

If you have specific questions on the presentations, please contact Klaus via mail: klaus.joehnk@csiro.au
as he - as the ASLO session organizer - is not present at the workshop

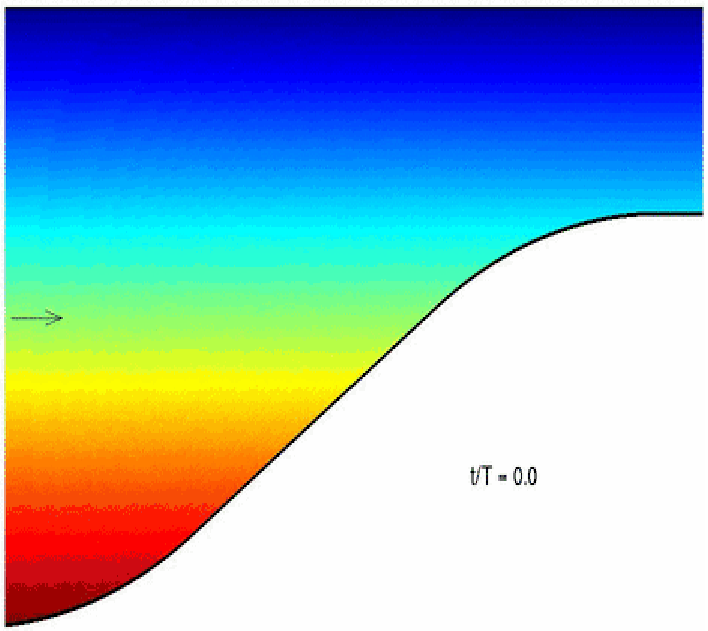
Modelling hydrodynamic processes in lakes

- The understanding of internal, hydrodynamic processes is essential to accurately simulate exchange with the atmosphere, on short (<hours) to large time scales (days, seasonal), e.g.
  - Surface water temperature
  - Ice cover
  - Gas exchange (CO_2, CH_4)

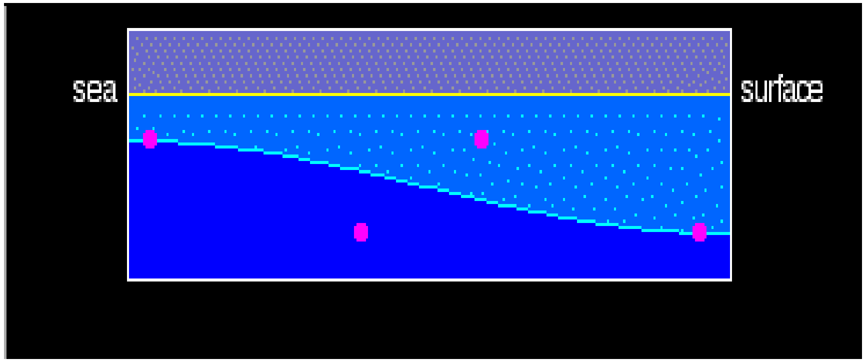
Sally MacIntyre – UCSB, USA
Capturing the consequences of non-linear internal waves in hydrodynamic models

Elisa Lindgren – U. Helsinki, Finland
Transmission of solar radiation through melting ice in an arctic lake

Sally MacIntyre, Capturing the consequences of non-linear internal waves in hydrodynamic models



Extent of wave breaking depends on thermocline tilt.
➔ Vertical fluxes result.
Predicted from Lake / Wedderburn number



$$W = \frac{g}{\rho}(\partial\rho)\left(h^2\right)/\left({u_{*_w}}^2 * L\right)$$

W drops to critical values when winds increase and density gradient decreases during cold fronts. L_N is an integral form of W.

Sally MacIntyre, Capturing the consequences of non-linear internal waves in hydrodynamic models

- Internal wave motions moderate shear at the top of the metalimnion.
- When 1 < W or L_N < 10, partial upwelling occurs with larger vertical exchanges near lateral boundaries
- When ~0.1 < W or L_N < 1 full upwelling with exchange between epi- and hypolimnion. Extent of exchange is not fully known, but causes errors particularly in 1 D models.
- Extent of vertical exchange depends on basin morphometry with larger fluxes when lake margins slope moderately rather than steeply.
- Modeling accuracy will be improved by inclusion or with improved parameterizations of these waves.

Elisa Lindgren, Transmission of solar radiation through melting ice in an arctic lake

- Convection is the strongest driver of under-ice mixing in spring, driven by solar radiation penetrating the ice.
- Transmission of solar radiation is critical for the heat and mass balance of lake ice, and for biological processes.
- Only few studies about transmissivity and ice structure of lakes have been performed, especially in the arctic regions.

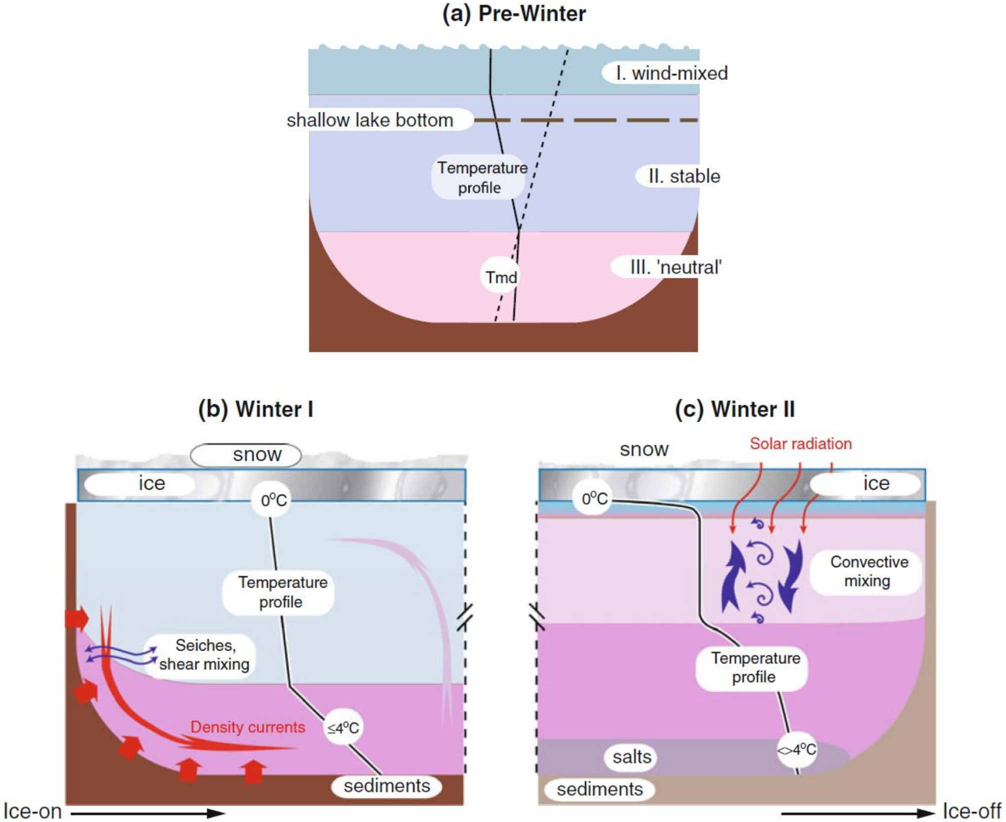
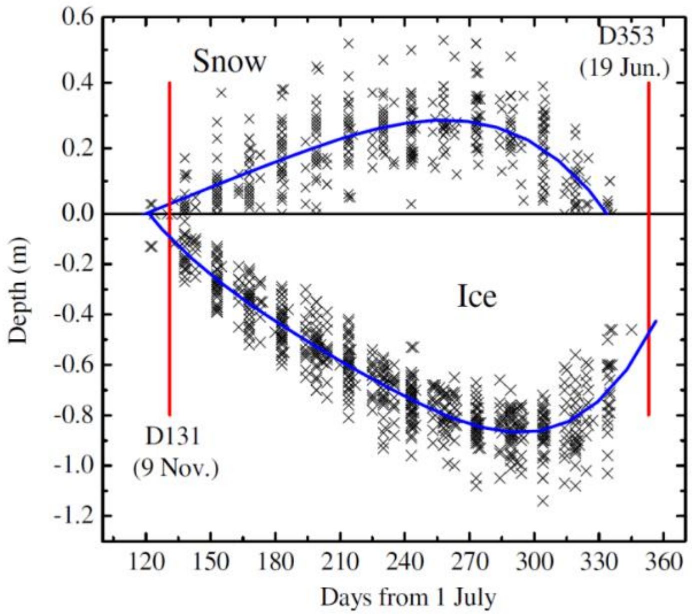


Fig. Adapted from Kirillin et al. (2012)



Snow depth (1972-2008) and ice thickness (1964-2008) at Lake Kilpisjärvi, Finland (Lei et al., 2012).

Elisa Lindgren, Transmission of solar radiation through melting ice in an arctic lake

- The amount of solar radiation penetrating the ice is high (transmittance 0.6-0.9) close to ice break-up and in the absence of snow and snow-ice
  - Explains the fast warming of the water
  - Light conditions favorable for primary production?
- Melting of congelation ice was fast (up to 4 cm per day)
  - Internal melting at the crystal boundaries produced candled ice
  - Accounts for the high transmittance
- In natural waters the ice sheet is far from homogeneous
  - Differential light conditions under the ice, melting, and heating of water

Fig 11. Lake Kilpisjärvi on 31st of May, 2013.

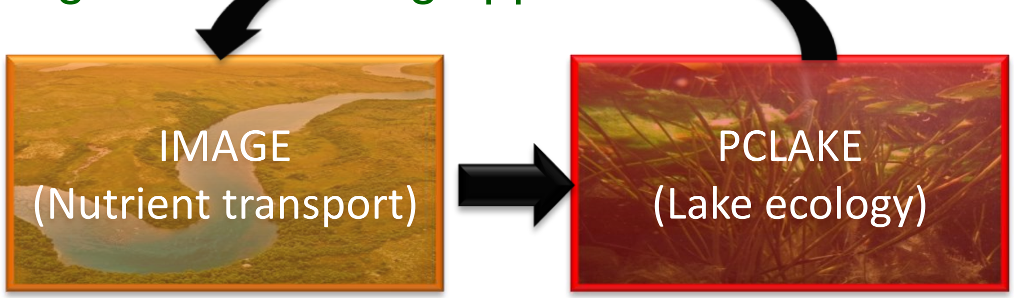
Coupling with ecosystem models

- Connecting ecosystem models with lake hydrodynamic models
- needs the knowledge of nutrient transport between connected systems (lakes, wetlands, streams)
- establish unified connectors between heterogeneous model environments

Annette Janssen - NIOO KNAW, Netherlands
Global variation in lake response to anthropogenic stresses: an integrated modeling approach

Thomas Bueche – LMU Munich, Germany
The mixing behaviour of a medium-sized lake in Southern Germany. A modeling approach by the implementation of the new community model GLM and FABM

Annette Janssen, Global variation in lake response to anthropogenic stresses: an integrated modeling approach

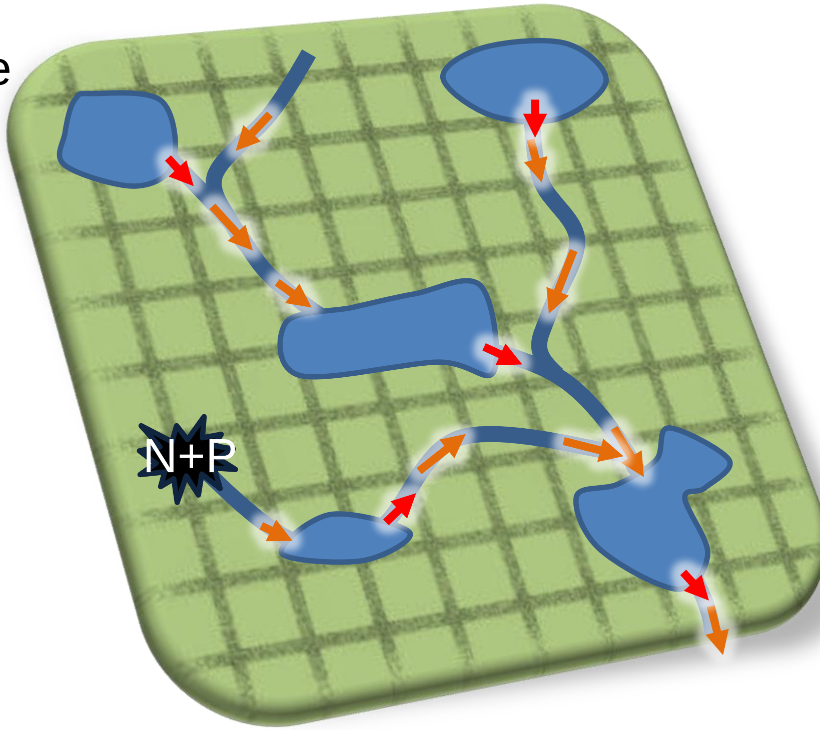


1. Anthropogenic pressures on lakes increase
   |->Lakes become eutrophic

2. Climate change prediction
   |->Why not algal blooming prediction?

3. Link lake ecology with nutrient transport
   |-> IMAGE + PCLake

4. Usage:
   |-> Investigate global variation
   |-> Scenario Analysis
   |-> Global management



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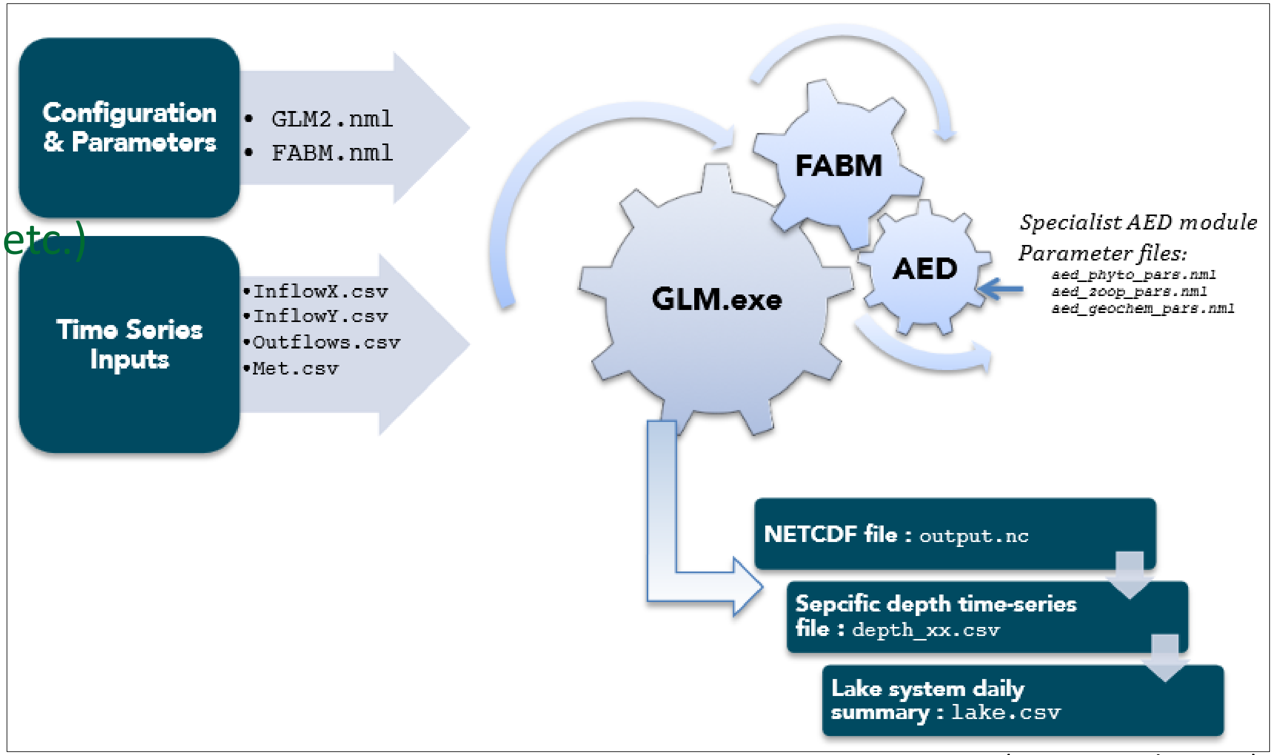
Thomas Bueche, The mixing behaviour of a medium-sized lake in Southern Germany

GML-FABM

GLM
(General Lake Model)
- Water temperatures (stratification, ice cover, etc.)
- Salinity

FABM
(Framework of Aquatic and Biochemical Models)
→AED modules
(Aquatic Ecodynamics)
- O_2, Nutrients, etc…
- Tracer (virtual)



(Hipsey et al., 2014)

Settings for Lake Ammersee

Simulation period:
four complete hydrological years + 10 months “warm-up“

Implemented inflow data (*inflow.csv*)
Dissolved oxygen, nitrogen (NO_3, NH_4), silica, phosphorus, DOC

Saison	Typ
2004/05	D2
2005/06	D2
2006/07	Mo
2007/08	Mo

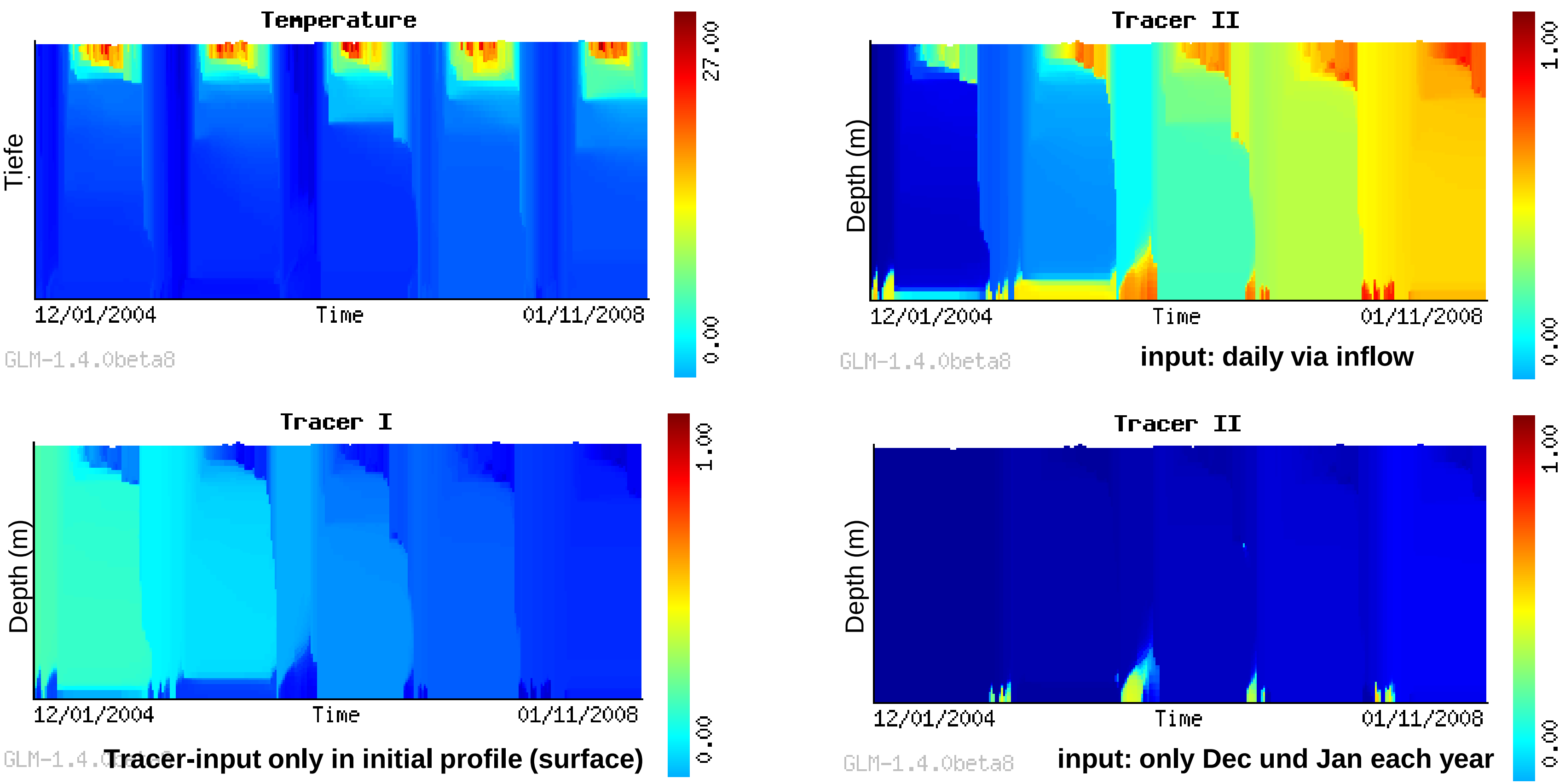
with ice cover

Thomas Bueche, The mixing behaviour of a medium-sized lake in Southern Germany

Simulation results Ammersee

Simulation of lake mixing using FABM tracer-tool (*aed_tracer*)

→ Definition in initial profile <u>and</u> input via inflow



Multi-lake and multi-model approaches

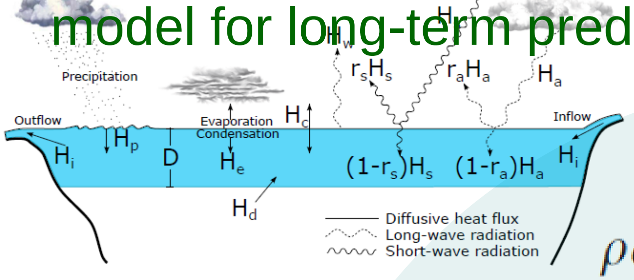
- Need simple, fast, and accurate simulation tools for e.g. long-term predictions
- Computer power can be utilized to manage large scale lake simulations (multi-lake)
- Model ensemble approaches can highlight differences in implemented processes
- Prediction of future lake states need weather generator

Marco Toffolon – U. Trento, Italy
How lakes respond to air temperature changes: a lumped model for long-term predictions

Koji Tominaga – U. Oslo, Norway
Physical status of lakes in Northern Europe for the next hundred years

Gideon Gal – IOLR, Israel
Ensemble modeling of the impact of increased frequency of climatic disturbances on a subtropical lake ecosystem

Marco Toffolon, How lakes respond to air temperature changes: a lumped model for long-term predictions



lake surface temperature

net heat flux

$$\rho c_p V_s \frac{\mathrm{d}T_w}{\mathrm{d}t} = \Phi_{net} A$$

surface area

surface layer volume

specific heat

water density

from surface heat budget…

… to ***air2water*** model

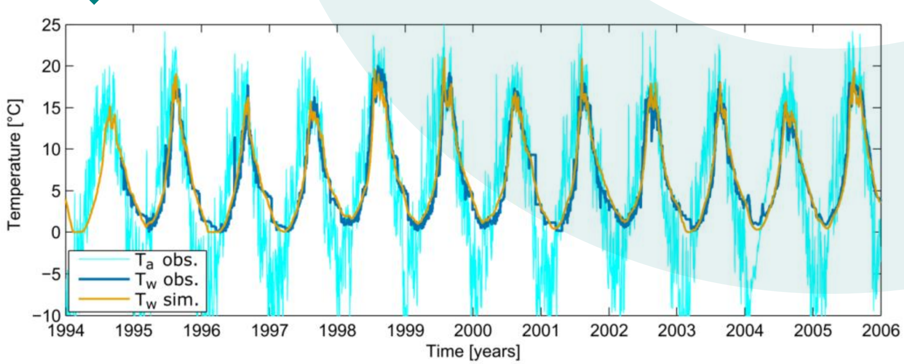
air temperature

$$\frac{\mathrm{d}T_w}{\mathrm{d}t} = \frac{1}{\delta}\left\{a_1 + a_2 T_a - a_3 T_w + a_5 \cos\left[2\pi\left(\frac{t}{t_y} - a_6\right)\right]\right\}$$

dimensionless surface layer volume (function of T_w and 3 parameters)

seasonal forcing term

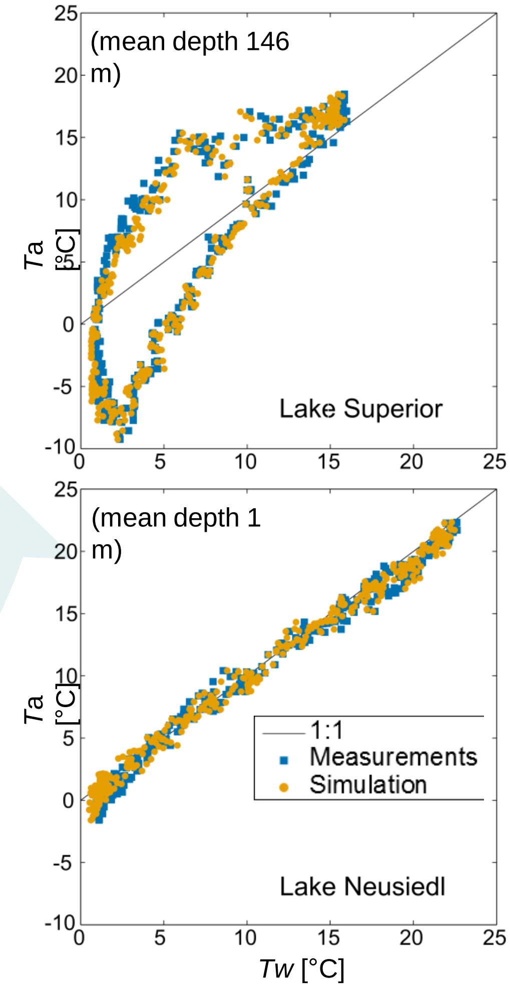
calibration of parameters with measurements



results comparable to physically-based models

Lake Superior RMSE =
1.17°C (calibration)
1.01°C (validation)

the model captures annual hysteresis in deep lakes



Piccolroaz, S., M. Toffolon, and B. Majone (2013), **A simple lumped model to convert air temperature into surface water temperature in lakes**, *Hydrology and Earth System Sciences, 17*(8), 3323-3338.

Toffolon, M., S., et al. (2014), **Prediction of surface temperature in lakes with different morphology using air temperature**, *Limnology and Oceanography, 59*(6), 2185-2202.

Koji Tominaga, Physical status of lakes in Northern Europe for the next 100 y

August lake water temperature in Norway, Sweden and Finland.

Warming or opening of ice is projected, and projection differs depending on

i) GHG concentration pathway and
ii) ii) regional climate model.

RCM KNMI

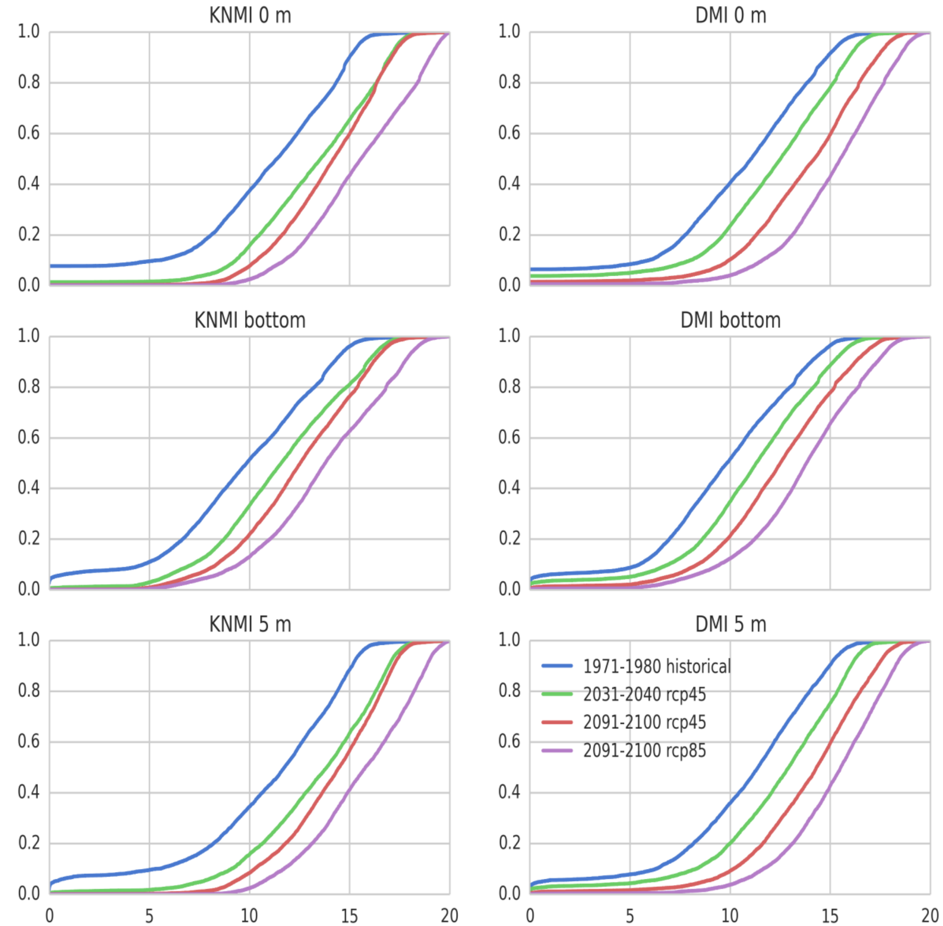
RCM DMI

Surface

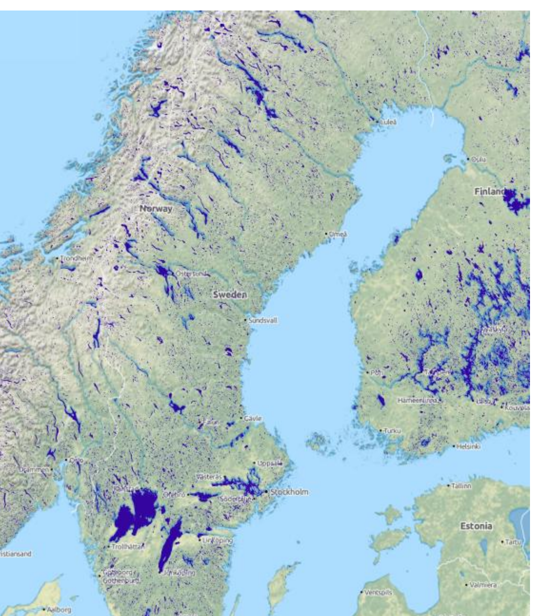
Bottom

4-5 m (if applicable)

Cumulative distribution



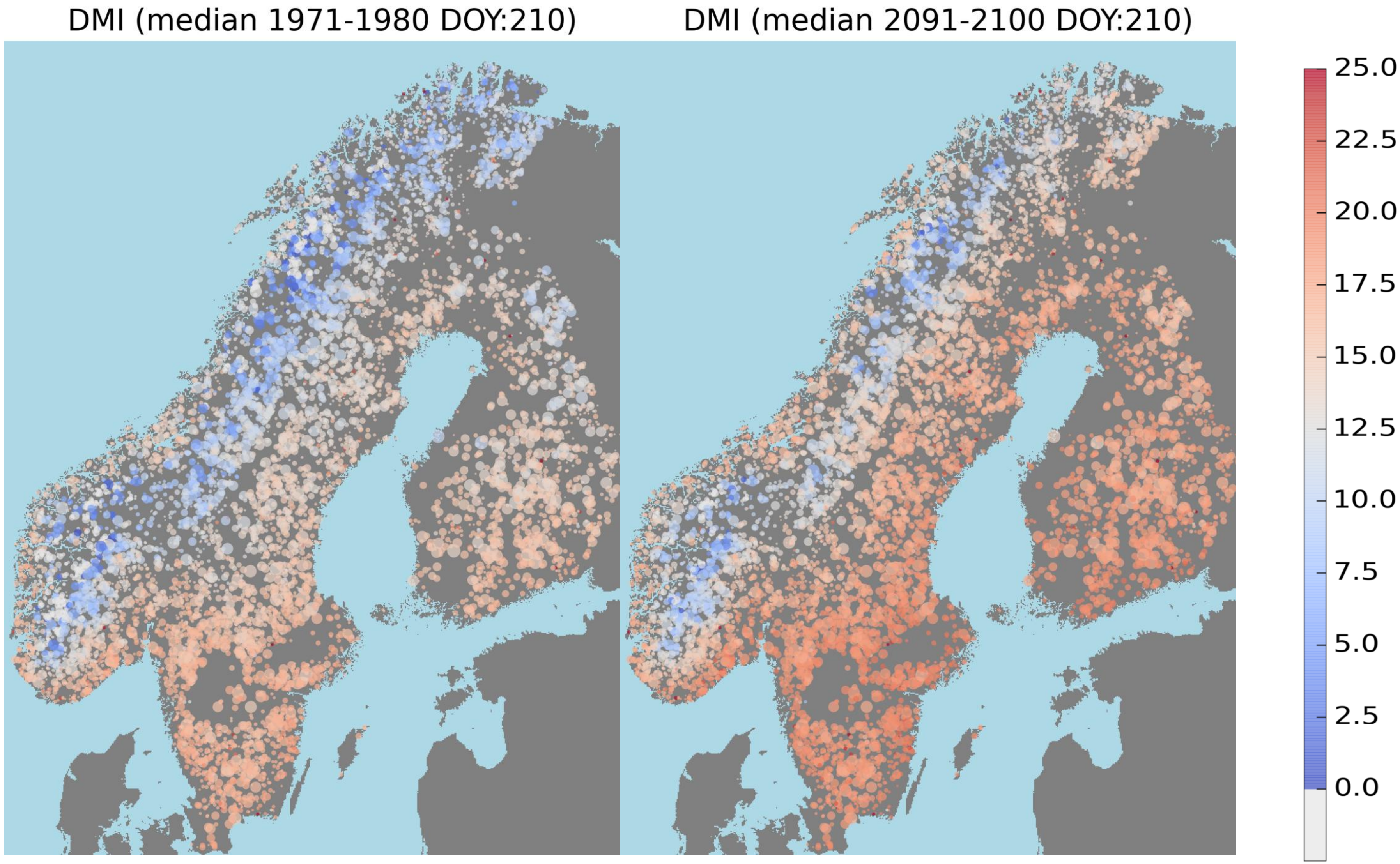
Water temperature



Koji Tominaga, Physical status of lakes in Northern Europe for the next 100 y

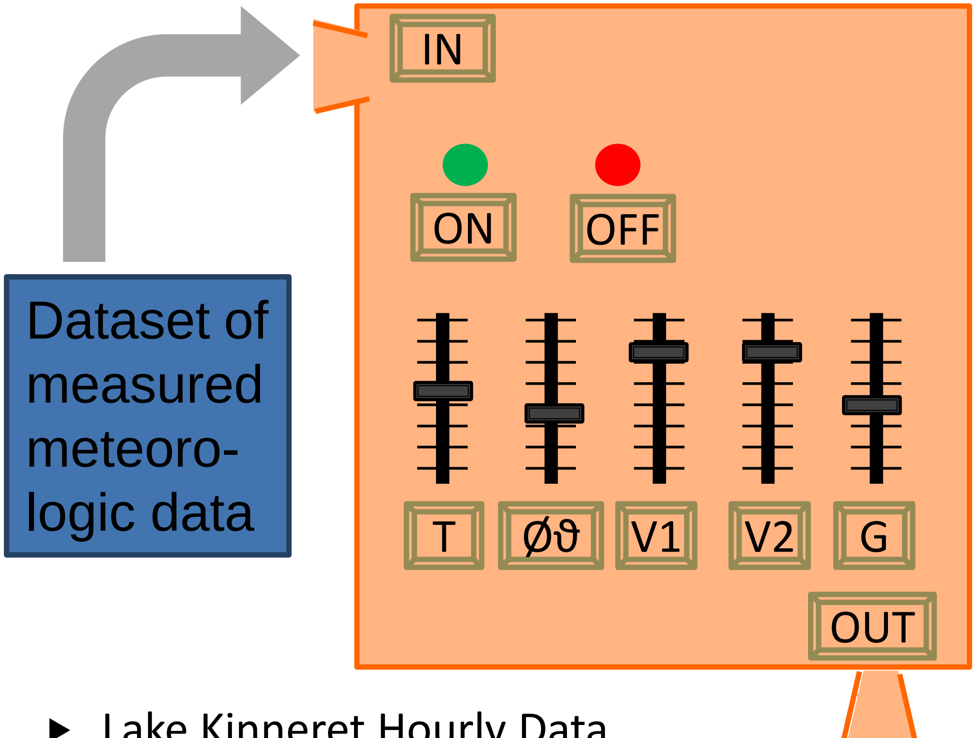
Late August lake surface water temperature in Norway, Sweden and Finland.

Projected warming throughout the region

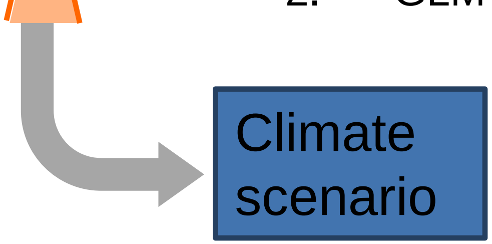


Gideon Gal, Ensemble modeling of the impact of increased frequency of climatic disturbances on a subtropical lake ecosystem

Vector-autoregressive weather Generator VG



- Lake Kinneret Hourly Data
- 1.1.1997- 31.12.2007
- Air temp., SW & LW radiation, vapor pressure, wind



Scenarios

1. Unchanged
2. Gradual: 2˚C increase over 30 years (2010-2039)
3. Spicy: increasing frequency of heat waves but no gradual increase
4. Gradual + heat waves (2 + 3)

- Total of 100 realizations of each scenario
- No interannual variation in gradual and unchanged scenarios
- 30 year simulations (2010-2039)
- Ensemble of 1-D Hydrodynamic models:
    1. DYRESM
    2. GLM

Coupling with regional climate models

- Several coupled models between lake and regional climate models or atmosphere models exist
- FLake is the most widely used candidate, but cannot fully handle lake internal hydrodynamic processes
- WRF CLM includes a Hostetler type lake model
- U. Geneva single column model use a k-epsilon turbulence lake model, SIMSTRAT
- The coupling is often only from climate model into the lake
- A better understanding for effects of lakes on the climate is necessary
- For large lakes a direct influence on regional climate is evident
- Two-way coupled lake – RCM or SCM needed

Coupling with regional climate models

Lijuan Wen – CAREERI, CAS, China
Impact of lake salinity on local climate with the WRF_CLM model

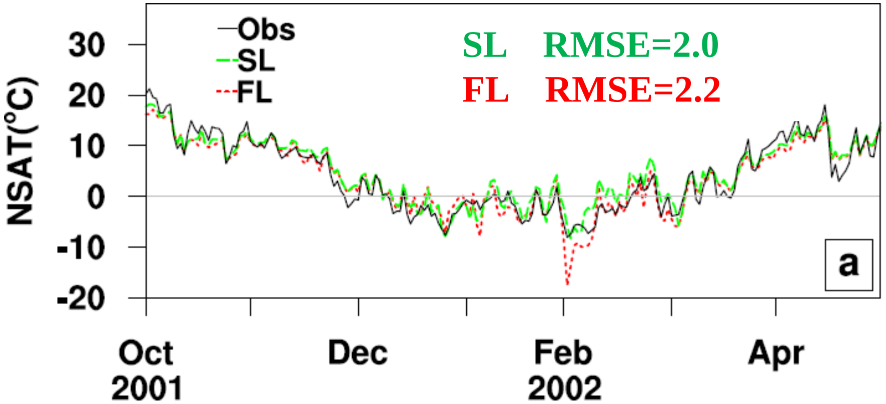
Wim Thiery – KU Leuven, Belgium
Modeling the influence of the African Great Lakes on the regional climate

Stephane Goyette – U. Geneva, Switzerland
On a single column atmospheric model framework to study lake processes: The case of deep Lake Geneva

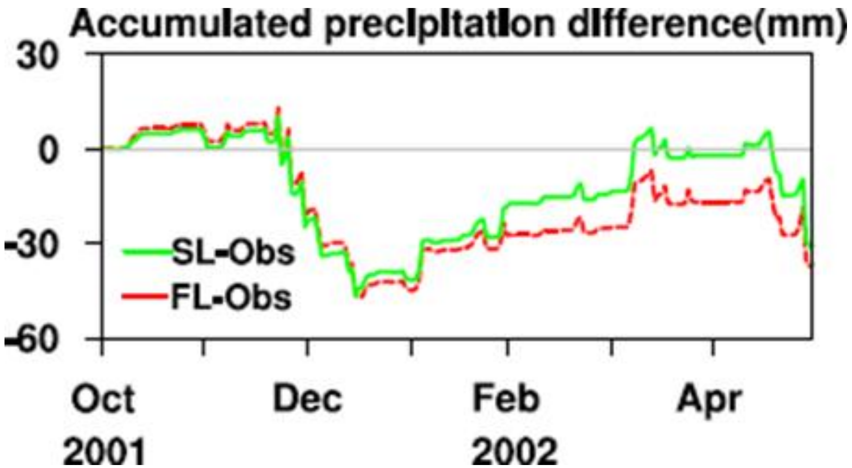
Marjorie Perroud – U. Geneva, Switzerland
Development and validation of a coupled single-column lake – atmospheric model to simulate thermal profiles in Lake Geneva

Observation and simulation over the Great Salt Lake

- ✓ SL: with salinity parameterizations
- ✓ FL: similar to SL experiment, but without salinity



SL and **FL** both caught variations of NSAT (near surface air temperature) well. But the simulated temperature was too low in the very cold event in FL.



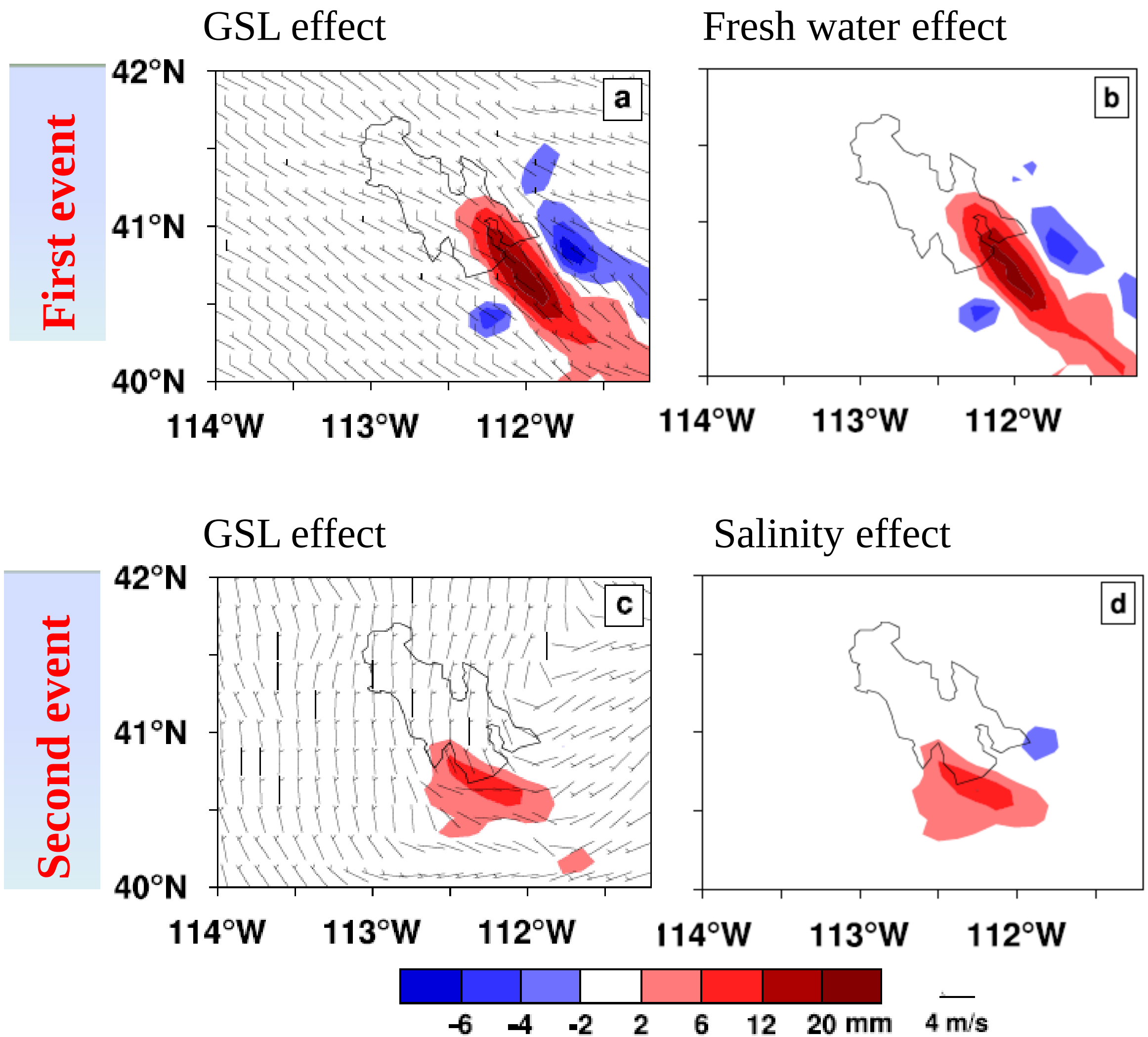
SL experiment had better precipitation simulation at Garfield station.

The WRF_CLM model with salinity parameterizations could more accurately simulate temperature over and in the GSL, and downstream precipitation of the GSL.

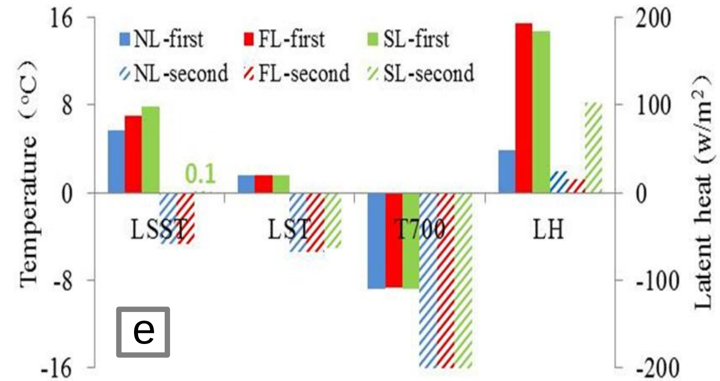
Lijuan Wen, Impact of lake salinity on local climate with the WRF_CLM model

GSL effect precipitation events

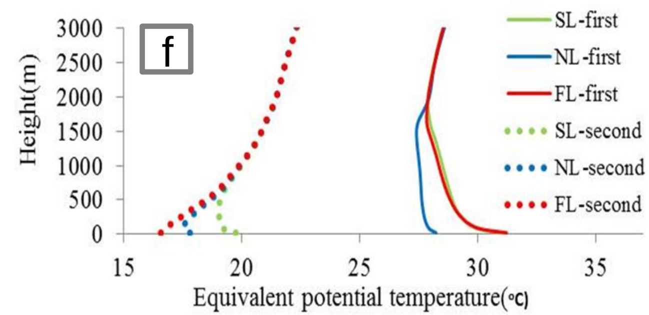
Precipitation



Temperature and latent heat flux of two events



Vertical equivalent potential temperature of two events



Wim Thiery – KU Leuven, Belgium

Modeling the influence of the African Great Lakes on the regional climate

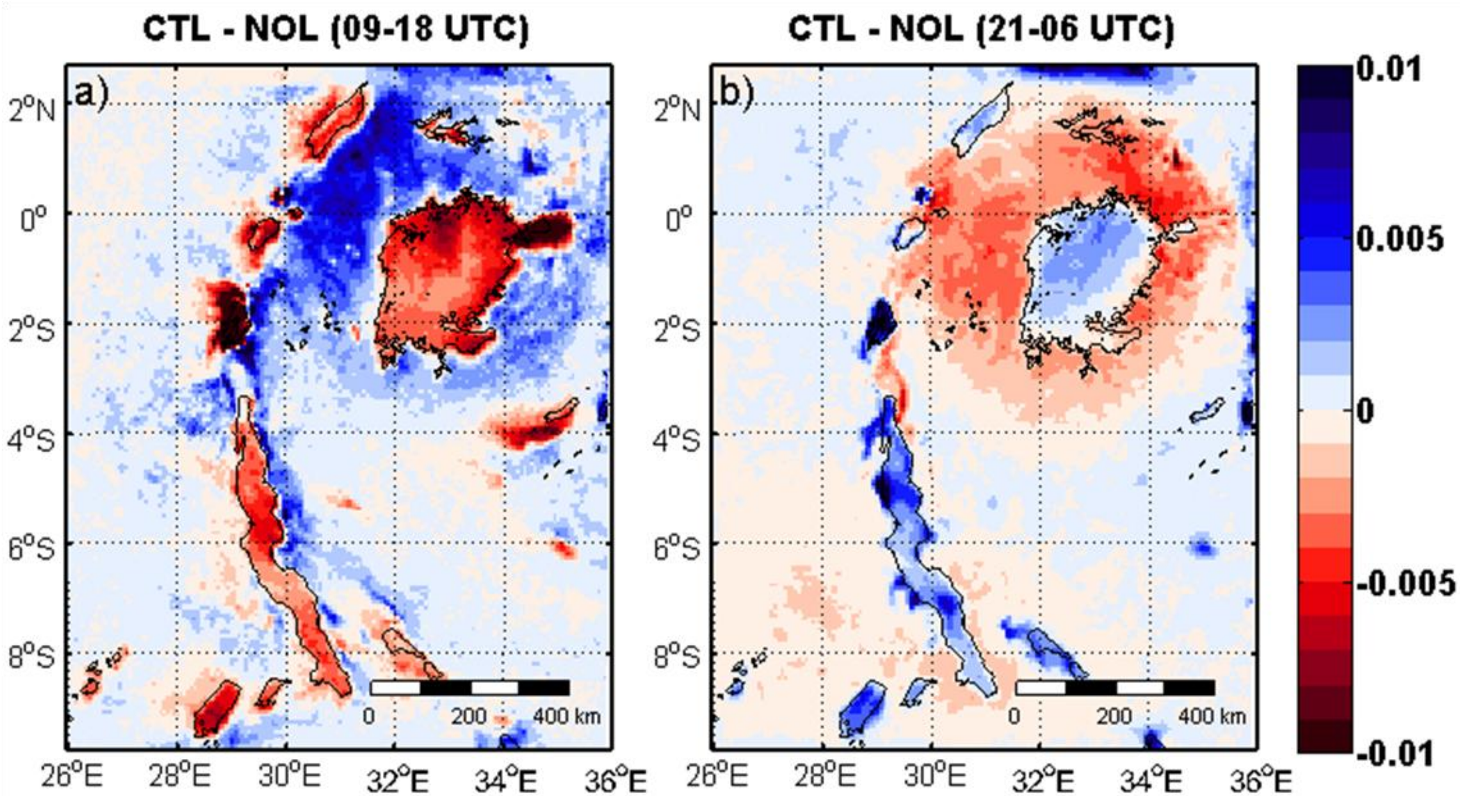
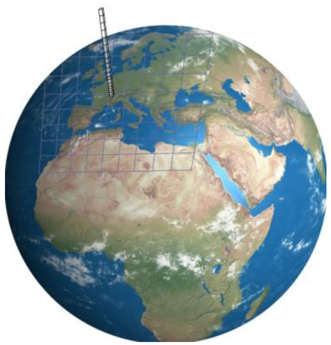


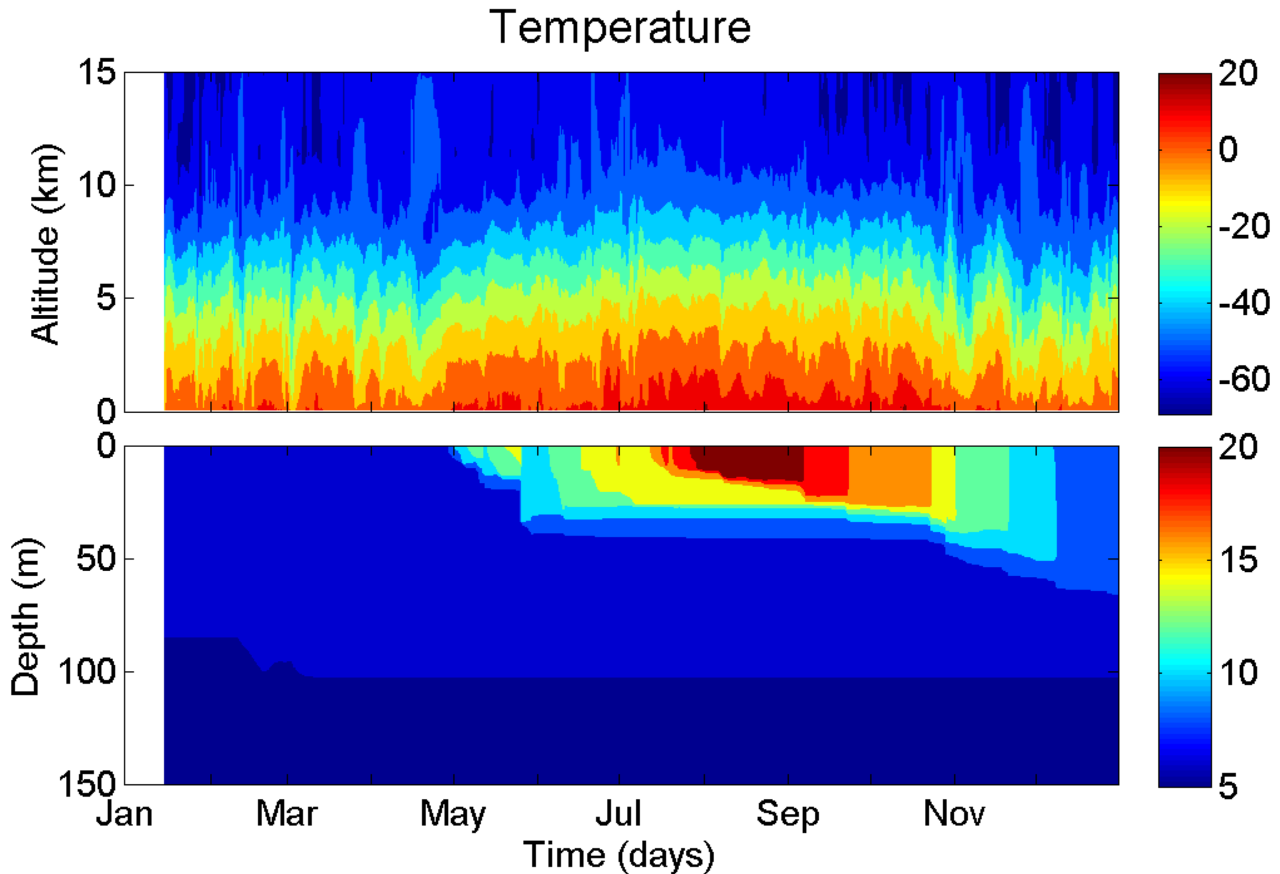
Figure 1. Evidence of lake impact on convective mass flux density

- **The AGL reduce offshore near-surface air temperature by about -0.57K and enhance precipitation by +732 mm yr-1 (+87%) over their surface.**
- **During daytime, the lake breeze transports cold air across the lake borders and generates over-land updrafts and over-lake subsidence, effectively suppressing convection from the unstable surface layer (Fig. 1a).**
- **At night, the thermal inertia of the lake surface generates a positive temperature anomaly and a pressure deficit, and maintains the daytime evaporation rates, inputting large amounts of moisture into the boundary layer (Fig. 1b).**

Marjorie Perroud, Development and validation of a coupled single-column lake – atmospheric model to simulate thermal profiles in Lake Geneva

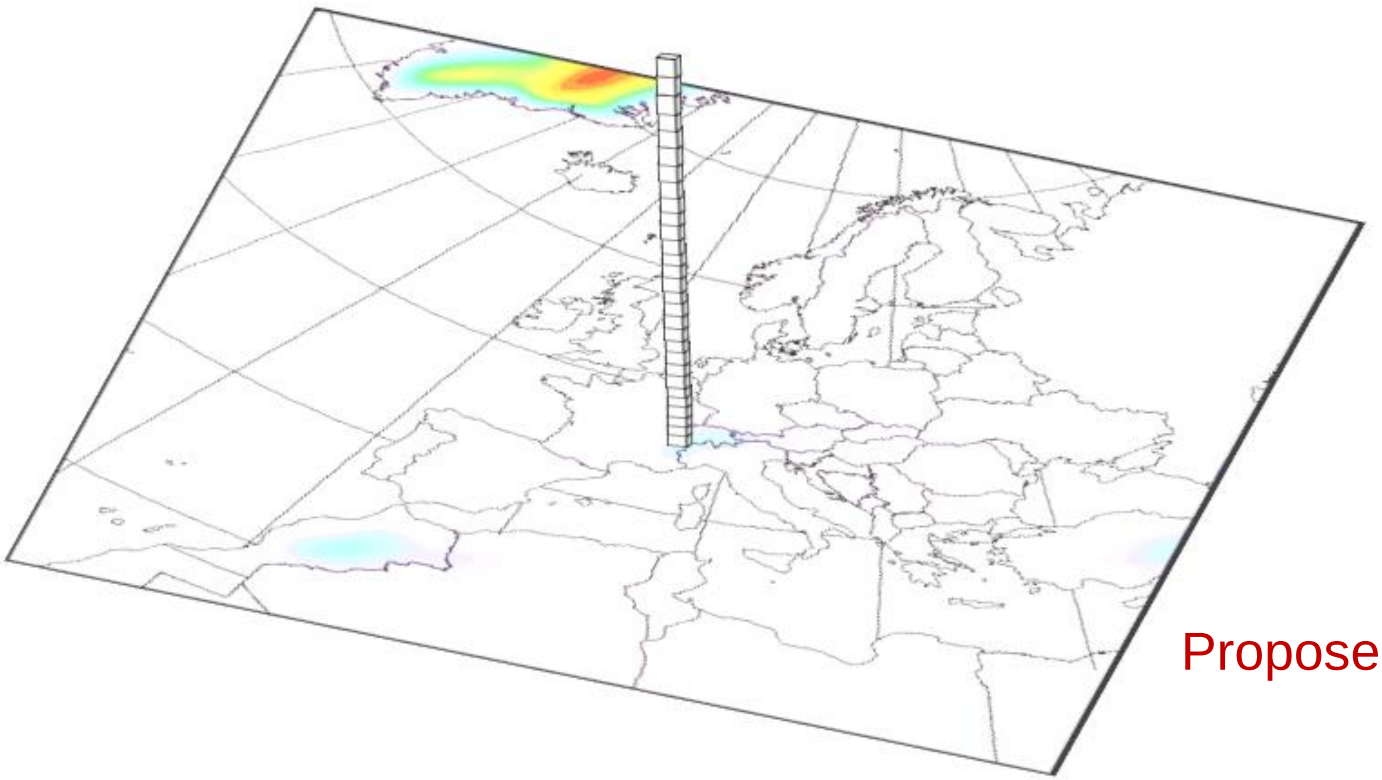
- A column embedded within the Canadian RCM grid over western Switzerland and coupled to lake model SIMSTRAT to simulate the thermal evolution of Lake Geneva
  - ➢ atmosphere driven by NCEP-NCAR reanalyses
- Simulated lake water temperature profiles under the simulated atmospheric profiles are rather realistic
  - ➢ some improvements related to coupler yet needed





Stéphane Goyette, On a single column atmospheric model framework to study lake processes: The case of deep Lake Geneva

- 60 km grid mesh (current computational domain below),
- 10 min timestep, 29 vertical levels, 6-hr archival frequency,
- few annual cycles are currently available but a long continuous run is planned (e.g. 1960 – 2014),
- land surface and a lake model (SIMSTRAT) available
- an option to use many lake models is planned



Proposed LakeMIP project

LakeMIP

1. Model ensemble (Klaus Joehnk)
2. Harp Lake model (Victor Stepanenko)
3. Single column model (Stéphane Goyette)
4. Fully coupled 3D lake-atmopshere RCM intercomparison (Wim Thiery)

Community publication

Challenges of modelling lakes as components of regional climate systems

1. Model ensemble (Klaus Joehnk)

- Use a large number of lake models to simulate a large number of lakes in different climate regions
- Determine differences in lake characteristics
  Surface temperature, stratification (thermocline depth), seasonal characteristics
- Use an all-models on all-lakes approach with a single set (per model) of parameters to test their generality
- Use a subset of well monitored lakes with all models individually calibrated to test specific model characteristics
- 16 lake models, 17 lakes (will be reduced to a set of 10).

LakeMIP model ensemble

Lake models and modellers

User/Developer	Model name	
Klaus Jöhnk	LAKEoneD	k-e
Victor Stepanenko	LAKE	k-e
Stéphane Goyette	SCM-Simstrat	k-e
Marjorie Perroud	Simstrat	k-e
Karsten Bolding	GOTM	k-e
NA	PROBE	k-e
Georgiy Kirillin, Wim Thiery	FLAKE	similarity
Deniz Özkundaci, Bertram Boehrer, Louise Bruce, Nihar Samal, Gideon Gal	GLM (two should switch to DYRESM?)	energy
Thomas Bueche Mark Vetter	DYRESM	energy
Jordi Prats	EOLE	bulk
Xing Fang	Minlake	bulk
Raoul Couture Koji Tominaga	MyLake	bulk
Brigitte Vincon-Leite, Bruno Lemaire, Frederic Soulignac	1DV	bulk
Huaxia Yao	Hostetler	bulk
Lijuan Wen Siguang Zhu	CLM	bulk
Marco Toffolon	air2water	empirical

LakeMIP model ensemble

Lakes

Valkea Kotinen, Finland
Kuivajärvi, Finland
Stechlin, Germany
Müggelsee, Germany
Kossenblatter Lake, Germany
Rappbode Reservoir, Germany
Ammersee, Germany
Lake Constance, Germany
Lake Geneva, Switzerland
Harp Lake, Canada
Lake Kivu, Africa
Lake Tanganyika , Africa
Ashokan Reservoir, USA
Otsego Lake, USA
Lake Kinneret, Israel
Toolik Lake , USA
Sparkling, USA

Lake in Nigeria
Norwegian Lakes (several)

2. Harp Lake model (Victor Stepanenko)

- Test the effect of stratification on the transport across the thermocline using different lake models
- Simulate gas exchange with the atmosphere in and out
- Test the effect of ice cover on gas exchange
- Focus on CO_2 and CH_4

3. Single column model (Stéphane Goyette)

- A Single Column Model for the atmospheric component will be used for an assessment of many lake models over a large variety of lake environments.
  This can be considered a necessary step before implementing a lake model within a particular RCM.
- One can use this approach to
  - assess many lake model performances over Lake Geneva (thermal profiles and other variables are available)
  - evaluate the impacts of feedbacks in the vertical dimension (a model option allows a "one-way" driven lake model as is the case when this model is driven by observations where no feedback is allowed)

  Lake models would need to be used as a FORTRAN subroutine within the Canadian RCM library.

4. **Fully coupled 3D lake-atmopshere RCM intercomparison (Wim Thiery)**

- Apply RCM with operational lake model to a region with large lakes (Laurentian or African Great Lakes, Baikal,...)
- Unify initial and lateral boundary conditions and horizontal resolution, and compare the output.

Participants

- Stéphane Goyette, CRCM5.
- Wim Thiery, CCLM².
- ! … more … !

Community publication

(titles will certainly change)

Challenges of modelling lakes as components of regional climate systems

- We could raise the interest of >15 scientist at ASLO
- Frontiers in Environmental Science – Interdisciplinary Climate Studies
  or Tellus A (open discussion)

Challenges in lake ice modelling

- We could raise the interest of ~5 scientist at ASLO (that was at 6pm on the last day ;)
- Frontiers in Environmental Science – Interdisciplinary Climate Studies

We welcome more participants. Please send mail to Klaus Joehnk

Thank you

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Moskow State University
Victor Stepanenko

and 11 co-authors